UCLA/04/TEP/19

DAMA Dark Matter Detection Compatible with Other Searches

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(Dated: May 27, 2004)

We present two examples of velocity distributions for light dark matter particles that reconcile the annual modulation signal observed by DAMA with all other negative results from dark matter searches. They are: (1) a conventional Maxwellian distribution for particle masses of 6 to 9 GeV; (2) a dark matter stream coming from the general direction of Galactic rotation (not the Sagittarius stream). Our idea is based on having a signal in Na, instead of I, in DAMA, and can be tested in the immediate future by CDMS-II (using Si) and CRESST-II (using O).

PACS numbers: 14.60.St, 98.80.Cq

The nature of dark matter is one of the fundamental problems of physics and cosmology. Popular candidates for dark matter are weakly interacting massive particles (WIMPs). Direct searches for dark matter WIMPs aim at detecting the scattering of WIMPs off of nuclei in a low-background detector. These experiments measure the energy of the recoiling nucleus, and are sensitive to a signal above a detector-dependent energy threshold.

One such experiment, the DAMA collaboration [1], has found an annual modulation in its data compatible with the signal expected from dark matter particles bound to our galactic halo [2]. Other such experiments, such as CDMS [3, 4], EDELWEISS [5], and CRESST [7, 8], have not found any signal from WIMPs. It has been difficult to reconcile a WIMP signal in DAMA with the other negative results.

Here we address this issue by posing the following question: is there a possible dark matter signal above threshold for DAMA and under threshold for CDMS and EDELWEISS, so that the positive and negative detection results would be compatible? The answer is yes.

We assume that dark matter consists of WIMPs whose mass and cross section we choose in a purely phenomenological way, without any attempt of providing an elementary particle model to support them.

The minimum dark matter particle velocity required to produce a certain nuclear recoil energy E is

$$v = \sqrt{\frac{ME}{2\mu^2}} = \sqrt{\frac{(m+M)^2 E}{2Mm^2}} \,, \qquad (1)$$

where $\mu = mM/(m+M)$ is the reduced WIMP-nucleus mass, m is the WIMP mass and M is the nucleus mass. The nuclear energy threshold $E_{\rm th}$ observable with a particular nucleus corresponds to a minimum observable WIMP velocity, the velocity threshold $v_{\rm th}$. Threshold energies for several direct detection experiments are collected in Table 1.

To make our argument as simple as possible, consider for a moment the case $m \ll M$. Then $\mu \simeq m$ is independent of the nucleus mass M, and $v_{\rm th}$ is proportional to $\sqrt{ME_{\rm th}}$. Using the nuclear masses of Na and Ge, $M_{\rm Na} = 21.41$ GeV and $M_{\rm Ge} = 67.64$ GeV, and the energy thresholds in Table 1, the product $ME_{\rm th}$ is smaller for Na in DAMA than for Ge in CDMS-I. For $m \ll M$, the $v_{\rm th}$ of CDMS-I is 2.44 times that of DAMA, and the $v_{\rm th}$ of CDMS-II and EDELWEISS (as well as those of other experiments using heavier nuclei) are larger. Using the full Eq. (1), it is easy to see that the velocity threshold of Na in DAMA is smaller than that of Ge in CDMS-I for $m < 22.3$ GeV.

This means that for light enough WIMPs it could be possible to have a virialized or non-virialized (a stream) halo component which could have a velocity above threshold for Na in DAMA, and below threshold for Ge in CDMS and EDELWEISS. That is, we could have a dark matter signal visible for DAMA but not observable by CDMS and EDELWEISS.

CDMS has a small component of Si too. Si is lighter than Ge, although heavier than Na, $M_{\rm Si} = 26.16$ GeV. Given the mentioned nuclear energy recoil thresholds, the velocity threshold of Si in CDMS-I is smaller than that of Na in DAMA for all WIMP mass values. However, considering the CDMS efficiency close to 5 keV energies is about 10%, the exposure of the Si detector of CDMS near threshold is about 0.3 kg-day, which may be too small to have detected the signal which DAMA might have seen though its Na. In any event, CDMS has not yet used its Si component to set limits on dark matter, but only to help in background rejection.

Light nuclei are used by CRESST, in particular O, $M_{\rm O} = 14.90$ GeV. CRESST-I [7] used sapphire (Al_2O_3), which besides O contains Al, similar in mass to Si. CRESST-I has set limits on dark matter with a very low nuclear recoil threshold of 0.6 keV, but with a small exposure of only 1.5 kg-day. The velocity threshold for O in CRESST-I is so low that CRESST-I is sensitive to the bulk of the halo dark matter particles we are proposing. CRESST-II uses calcium tungstate ($CaWO_4$), which also contains the light O nucleus, but background discrimination sets a relatively high threshold of ~ 10 keV. CRESST-II has run a prototype without neutron shield

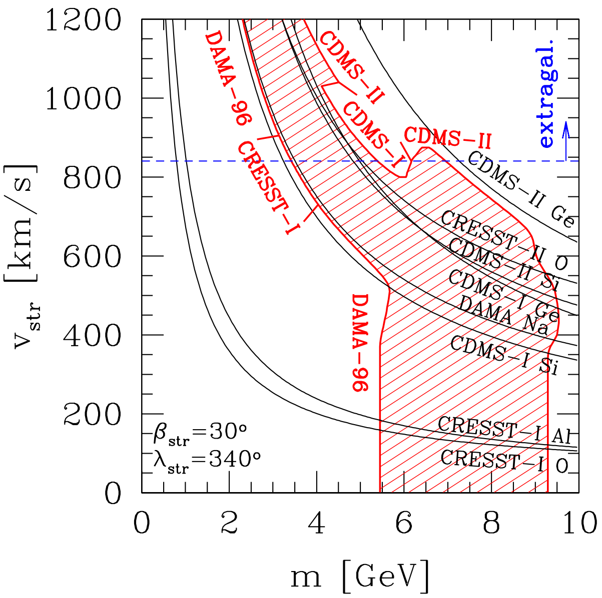

FIG. 1: Stream heliocentric speed $v_{\rm str}$ (here assumed to arrive from ecliptic latitude $\beta_{\rm str} = 30^\circ$ and ecliptic longitude $\lambda_{\rm str} = 340^\circ$) vs. WIMP mass m. The hatched region is compatible with DAMA, CDMS, EDELWEISS, and CRESST. Which experiment limits the compatible region is indicated along its edges. Also marked are the speed above which the stream is extragalactic (dashed horizontal line), and the threshold speeds $v_{\rm th}$ of several experiments and target nuclei.

and set the limits quoted in Table 1 [8]. The completed CRESST-II will test our idea.

Fig. 1 shows the relevant velocity thresholds $v_{\rm th}$, as functions of the WIMP mass m. Our idea is that a contribution to the density of WIMPs with velocities smaller than the CDMS threshold but larger that the DAMA threshold could explain the data. We are here thinking in terms of a non-virialized stream of dark matter [9] added to an isothermal halo model. The stream would be the dominant signal in DAMA (because there would be few halo WIMPs above the DAMA threshold) while it would change the signal due to the bulk of the halo (e.g. in CRESST) very little. The vertical axis of Fig. 1 gives the average dark matter stream velocity relative to the Sun. Assuming a stream as described below, the region where our idea works is the hatched region in the figure. To our surprise, the allowed region reaches zero stream velocity in a small interval of WIMP masses near 6 to 9 GeV. In this interval, a stream is not necessary and just the contribution of an isothermal halo would do.

If there is no halo contribution above threshold in DAMA, the stream arrival direction is limited by the requirement that the DAMA modulation peaks May 21 ± 22 days. May 21 is 61 days after the Spring equinox (March 21), and thus the Sun is at ecliptic longitude $61/365.25 \times 360 = 60^\circ$. Since the radius vector to the Sun and the velocity of the Earth are perpendicular (for a circular orbit), the Earth is moving toward a point of ecliptic longitude $60^\circ - 90^\circ = 330^\circ$. Thus, in case the DAMA modulation is entirely due to a dark matter stream, the arrival direction of the stream on Earth must have ecliptic longitude $\lambda = 330^\circ \pm 22^\circ$. The amplitude of the modulation depends on the projection of the stream velocity onto the ecliptic, and is proportional to $\cos\beta_{\rm str}$, where $\beta_{\rm str}$ is the ecliptic latitude of the stream arrival direction.

The non-virialized dark matter stream we are proposing could be bound to our galaxy or not. There are non-virialized dark matter streams bound to our own galaxy, such as the tidal streams of the Sagittarius dwarf galaxy [10]. The Sagittarius leading tidal stream passes through the solar neighborhood, with a heliocentric speed of ≈ 350 km/s, but its arrival direction $(\lambda, \beta) \approx (187^\circ, 8^\circ)$ does not have the correct ecliptic longitude to give the observed phase of the DAMA modulation without a substantial contribution from the usual halo component. So the stream we are implying should be a different, yet undiscovered, stream. There may be dark matter bound not to our galaxy but to our Local Group of galaxies [11], and also dark matter bound to our supercluster, possibly passing through us [12]. Its galactocentric incoming velocity $v_{\rm in}$ is increased by gravitational focusing while falling into our galaxy to become a galactocentric velocity $v_{\rm local} = \sqrt{v_{\rm in}^2 + v_{\rm esc}^2}$ near the Sun. Here $v_{\rm esc}$ is the local escape velocity from the Galaxy. The density of an incoming stream is also increased by focusing, at least linearly with the ratio $v_{\rm local}/v_{\rm in}$, but possibly by much larger factors, which are however complicated to evaluate. Interestingly, the Sun moves relative to the Local Group at 306 ± 18 km/s in direction $(\lambda, \beta) = (4^\circ \pm 10^\circ, 57^\circ \pm 4^\circ)$ [14], the ecliptic longitude of which is not far from the desired value.

Our procedure is the following. For the WIMP velocity distribution, we take $f(\mathbf{v}, t) = f_{\rm h}(\mathbf{v}, t) + f_{\rm str}(\mathbf{v}, t)$, the sum of a halo distribution $f_{\rm h}(\mathbf{v}, t)$ and an optional contribution from a dark matter stream $f_{\rm str}(\mathbf{v}, t)$. For $f_{\rm h}(\mathbf{v}, t)$ we take the conventional truncated Maxwellian used in the comparison of direct detection experiments,

$$f_{\rm h}(\mathbf{v}, t) = \frac{1}{N_{\rm h}(\pi \overline{v}_{\rm h}^2)^{3/2}} e^{-|\mathbf{v} + \mathbf{v}_\odot + \mathbf{v}_\oplus(t)|^2/\overline{v}_{\rm h}^2}, \qquad (2)$$

for $|\mathbf{v} + \mathbf{v}_\odot + \mathbf{v}_\oplus(t)| < v_{\rm esc}$, and $f_{\rm h}(\mathbf{v}, t) = 0$ otherwise. Here $N_{\rm h} = {\rm erf}(z) - 2\pi^{-1/2} z e^{-z^2}$, with $z = v_{\rm esc}/\overline{v}_{\rm h}$, is a normalization factor, $\mathbf{v}_\odot$ is the velocity of the Sun relative to the Galaxy (galactocentric velocity), and $\mathbf{v}_\oplus(t)$ is the velocity of the Earth relative to the Sun. For $\mathbf{v}_\odot$, we take the conventional value $v_\odot = 232$ km/s, which is within the measured value of 233±3 km/s in the direction $(\lambda, \beta) = (341^\circ \pm 1^\circ, 60.5^\circ \pm 0.5^\circ)$ [13]. For $\mathbf{v}_\oplus$, we assume a magnitude of 29.8 km/s along a circular orbit on a plane inclined by 60° with respect to $\mathbf{v}_\odot$. Furthermore, we take the conventional velocity dispersion $\overline{v}_{\rm h} = 220$ km/s and the escape speed from the galaxy $v_{\rm esc} = 650$ km/s. We make no claim that this is a realistic velocity distribution, but it offers us a definite benchmark for comparison. In addition, we assume the conventional value for the local dark matter density $\rho = 0.3$ GeV/cm^3. With the halo

Experiment	Exposure [kg-day]	Threshold [keV]	Efficiency [%]	Constraint	Ref.
CDMS-I	Si: 2.83 Ge: 28.3	5	$E<10$keV: 7.6 $E<20$keV: 22.8 $E>20$keV: 38	5–55keV: <2.3 events (†)	[3]
CDMS-II	Si: 5.26 Ge: 52.6	10	$E<20$keV: 22.8 $E>20$keV: 38	10–100keV: <2.3 events (†)	[4]
EDELWEISS	Ge: 8.2	20	100	20–100keV: <2.3 events (†)	[5]
CRESST-I	Al_2O_3: 1.51	0.6	100	(‡)	[7]
CRESST-II	$CaWO_4$: 10.448	10	100	Ca+O, 15–40keV: <6 events W, 12–40keV: <2.3 events (†)	[8]
DAMA/NaI-96	NaI: 4123.2	I: 22 (⋄) Na: 6.7 (⋄)	100	1–2keVee: <1.4/kg-day-keVee (⋆) 2–3keVee: <0.4/kg-day-keVee (⋆)	[6]
DAMA/NaI-03	NaI: 107731	I: 22 (⋄) Na: 6.7 (⋄)	100	2–4keVee: 0.0233±0.0047/kg-day-keVee (•)	[1]

TABLE I: Experimental constraints used in this study. Notes to the table: (†) upper limit assuming no detected event; (‡) to reproduce the published curve in [7], we impose appropriate upper limits all along the recoil spectrum in their Fig. 1; (⋄) from an electron equivalent threshold of 2 keVee, using the quenching factors $Q = E_{\rm ee}/E$ equal to 0.09 for I and 0.3 for Na [1]; (⋆) approximations that reproduce the published $\sigma_{\rm p}$ vs. m limit across our mass range; (•) amplitude of annual modulation.

model we assume, the maximum possible heliocentric velocity of a halo particle is $v_{\rm esc} + v_\odot = 882$ km/s.

For the stream, we assume

$$f_{\rm str}(\mathbf{v}, t) = \frac{\xi_{\rm str}}{(\pi \overline{v}_{\rm str}^2)^{3/2}} e^{-|\mathbf{v} - \mathbf{v}_{\rm str} + \mathbf{v}_\oplus(t)|^2/\overline{v}_{\rm str}^2}, \qquad (3)$$

where $\xi_{\rm str}$ is the local dark matter density in the stream (in units of 0.3 GeV/cm^3), $\mathbf{v}_{\rm str}$ is the stream velocity relative to the Sun (heliocentric velocity), and $\overline{v}_{\rm str}$ is the velocity dispersion in the stream (which we fix at 20 km/s; our results depend very little on the value of $\overline{v}_{\rm str}$). To produce Figs. 1 and 2, we take $\xi_{\rm str} = 0.03$ and a stream arrival direction $(\lambda_{\rm str}, \beta_{\rm str}) = (340^\circ, 30^\circ)$, so that the stream is at 30° of the ecliptic and at 30° of the Sun's galactocentric velocity. Such a stream is extragalactic if its heliocentric velocity exceeds 840 km/s (marked by the dashed horizontal line in Fig. 1). Due to gravitational focusing, to obtain $v_{\rm local} > 660$ km/s, for example, i.e. a stream heliocentric radial velocity $v_{\rm str} > 892$ km/s, requires $v_{\rm in} > 114$ km/s, a reasonable value.

For each choice of WIMP velocity distribution, we must make sure that we not only produce the correct amplitude for the DAMA modulation in the viable region but also that all of the current experimental constraints are satisfied. We consider constraints from DAMA/NaI-96 [6], DAMA/NaI-03 [1], CDMS-I [3], CDMS-II [4], CRESST-I [7], and CRESST-II [8]. The exposures, efficiencies, thresholds, and constraints we use are listed in Table 1.

We compute the expected number of recoil events with recoil energy in the range (E_1, E_2) as

$$N = \sum_i \int_{E_1}^{E_2} \frac{dR_i}{dE} \, \mathcal{E}_i(E) \, dE. \qquad (4)$$

The sum runs over the nuclear species in the detector, and $\mathcal{E}_i = \mathcal{M}_i T_i \epsilon_i(E)$ is the effective exposure of species i (T_i being the time the mass $\mathcal{M}_i$ is exposed to the signal, and $\epsilon_i(E)$ being the efficiency). Moreover, dR_i/dE is the expected recoil rate per unit detector mass and unit time,

$$\frac{dR_i}{dE} = \frac{\rho \sigma_i |F_i(E)|^2}{2 m \mu_i^2} \int_{v > \sqrt{M_i E / 2\mu_i^2}} \frac{f(\mathbf{v}, t)}{v} \, d^3 v. \qquad (5)$$

Here M_i is the nuclear mass, $\mu_i = m M_i/(m + M_i)$ is the reduced WIMP-nucleus mass, ρ is the local halo WIMP density, $F_i(E)$ is a nuclear form factor, σ_i is the WIMP-nucleus cross section, and $f(\mathbf{v}, t)$ is the WIMP velocity distribution in the reference frame of the detector.

In this analysis, we assume that the WIMP-nucleus interaction is spin-independent and scales with the square of the nucleus atomic number A_i as $\sigma_i = \sigma_{\rm p} A_i^2 (\mu_i/\mu_{\rm p})^2$. Here $\sigma_{\rm p}$ is the WIMP-proton cross section. For the nuclear form factor we use the conventional Helmi form, $F_i(E) = 3 e^{-q^2 s^2/2} [\sin(qr) - qr\cos(qr)]/(qr)^3$, with $s = 1$ fm, $r = \sqrt{R^2 - 5s^2}$, $R = 1.2 A^{1/3}$ fm, $q = \sqrt{2 M_i E}$.

To find a compatible region, we vary the WIMP mass, the stream density, and the stream velocity (allowing also for the absence of the stream). For each choice of these variables we find the WIMP-proton cross section $\sigma_{\rm p}$ that produces the desired modulation amplitude in the 2-4 keVee bin of DAMA/NaI-03 within two sigma (the resulting $\sigma_{\rm p}$ are shown in Fig. 2; we tried other ways to fix $\sigma_{\rm p}$ using also the 2-5, and 2-6 keVee bins and obtained similar results). With this WIMP-proton cross section, we evaluate the expected number of events in all of the other experiments. We thus determine if the parameters we choose are compatible with the experimental constraints we impose.

Fig. 1 shows the compatible region in heliocentric stream speed versus WIMP mass resulting from our study, cut arbitrarily to $v_{\rm str} < 1200$ km/s. The region is bounded from above by the constraints from CDMS-I and II, and from below by the constraint from DAMA/NaI-96 and CRESST-I, up to masses of about 6 GeV. The vertical band around $m = 6$ to 9 GeV shows that there the stream speed can be arbitrarily small. Indeed, in that mass range, the DAMA modulation can be reproduced

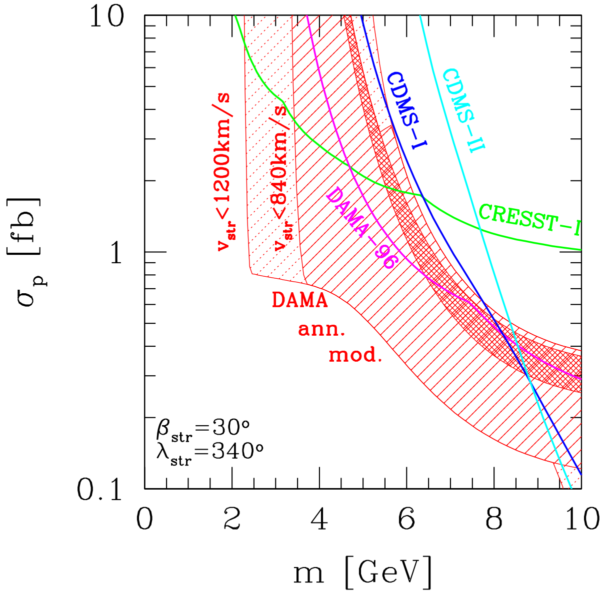

FIG. 2: Region of WIMP-proton cross section σ_p resulting from our study vs. WIMP mass m (cross-hatched region: without stream; hatched region: with stream and velocity cuts as shown). Also limits from DAMA/NaI-96, CRESST-I and II, and CDMS-I and II (see Table 1).

with just the conventional Maxwellian distribution, without an additional stream.

The hatched region in Fig. 2 shows the values of the WIMP-proton cross section σ_p resulting from our study that are compatible with the DAMA/NaI-03 modulation, as a function of the WIMP mass. The region was cut arbitrarily at $v_\mathrm{str} < 1200$ km/s, as in Fig 1. Also shown is where the cut would be for a Galactic stream, $v_\mathrm{str} < 840$ km/s. The cross-hatched region is the case of a conventional Maxwellian halo without a stream. The upper bounds on σ_p are given by CRESST-I, CDMS-I and II, and DAMA/NaI-96. The values we find are included in the region presented as allowed by DAMA in Fig. 28 of Ref. [1]. Light neutralinos as WIMPs with masses as low as 2 GeV [15] or, with updated bounds, 6 GeV [16] have been considered, but their cross sections are about one order of magnitude smaller than those needed here.

In conclusion, we have pointed out that for light dark matter particles a signal could be observed by DAMA through its Na component. This signal would be below threshold for Ge in CDMS and EDELWEISS. This possibility can be tested with a few months of Si data in CDMS-II, and future O data in CRESST.

For WIMPs with spin independent interactions, we have presented two examples of dark matter velocity distributions that give the annual modulation observed by DAMA but satisfy all other constraints from dark matter searches. The first is a conventional Maxwellian distribution with a WIMP mass around 6 to 9 GeV. Surprisingly, this simple possibility remains open. Our second example is the former distribution superposed to a dark matter stream coming from the general direction of the Galactic rotation (perhaps associated with extragalactic dark matter, but *not* the Sagittarius stream).

For the sake of illustration, we have assumed a particular density of the stream (0.03 of the local halo density) and a particular incoming direction (halfway between the plane of the Earth's orbit and the direction of the Sun's velocity in the Galaxy). Our main result are the allowed regions presented in Figs. 1 and 2.

Clearly, the effect of the stream would be larger (smaller) for larger (smaller) stream densities and for incoming directions closer to (further from) the plane of the Earth's orbit. For simplicity, we have illustrated our idea only for the case of WIMPs with spin-independent interactions. Other kinds of particles and interactions, or halo velocities distributions more complicated than a conventional Maxwellian distribution, may extend the allowed regions of parameters.

This work was supported in part by the US Department of Energy Grant DE-FG03-91ER40662, Task C and NASA Grant NAG5-13399.

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